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NASA
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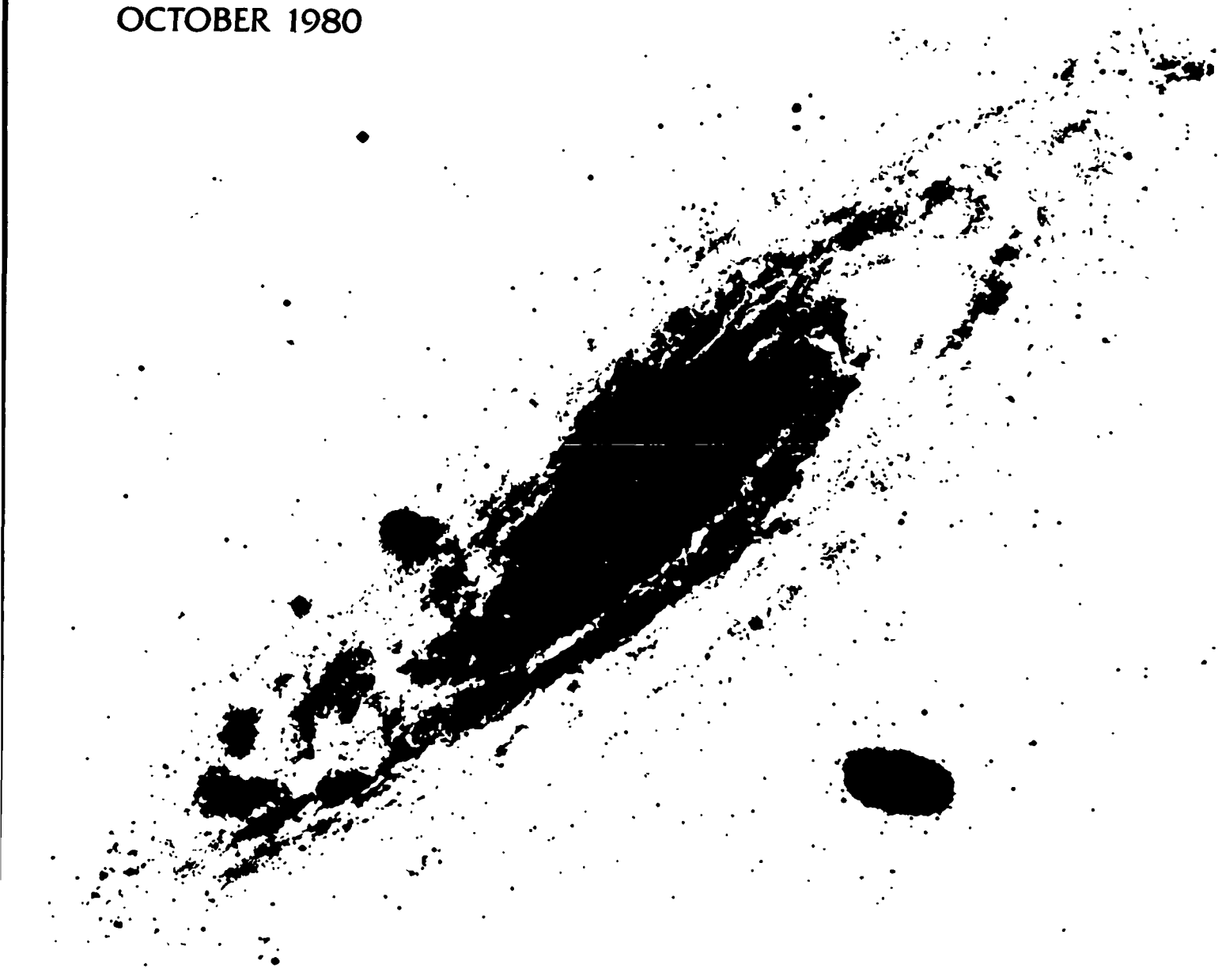
ASTROPHYSICS PROGRAM

PROJECT CONCEPTS:

Gravitational Radiation Searches and Gravitational Wave Astronomy

OCTOBER 1980



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FOREWORD

This document is one in a series describing projects of current interest in NASA astrophysics planning. Some of these projects were originally suggested by the Space Science Board of the National Academy of Sciences and the Outlook for Space Study Group. Others have been suggested by various internal working groups. Still others have been suggested by individual scientists or scientific groups both within NASA and in the broad astrophysics community. The descriptions presented in these volumes are based on technical studies or preliminary assessments done by NASA's Ames Research Center, Goddard Space Flight Center, Marshall Space Flight Center, and the Jet Propulsion Laboratory. Since the projects are at various stages in the planning process, the level of detail presented gives our current best estimate of the scientific objectives and technical characteristics. Where variations such as alternative strawman payload combinations have been studied, these are presented, and their effects on the overall project are discussed. Specific spacecraft, and other systems or subsystems, are identified or implied in many cases to illustrate that a concept for conducting the project exists. Such identification does not reflect a commitment on the part of NASA to utilize such hardware should the project be implemented. Similarly, in the actual implementation of any particular project, details will inevitably change. Our objective in assembling these documents has been to produce a set of concise project descriptions in a uniform format. They are intended to serve as a basis for discussion within the astrophysics community and to help determine how individual missions can best be accommodated within NASA's overall astrophysics program.

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Table of Contents

Foreword 2

Overview 5

Introduction 6

Science 6

Detection Techniques 8

Precision Doppler Tracking of Nondedicated Interplanetary Spacecraft 10

Doppler and Ranging Transponder (DART) Mission 11

Hydrogen Maser Gravitational Wave Mission 15

Laser Heterodyne Gravitational Wave Mission 19

Laser Interferometer Gravitational Wave Mission 21

GRAVITATIONAL RADIATION SEARCHES AND GRAVITATIONAL WAVE ASTRONOMY

OVERVIEW

This brochure describes several experimental concepts and missions which have the common objective to search for gravitational radiation. Two different detection techniques are under consideration involving radio Doppler tracking and laser systems. The technology required for the radio Doppler method is practically available. Missions employing this technique could be implemented in the near future. Missions utilizing laser techniques require substantial technology development before implementation details can be defined. No commitment has been made to fly the missions and experiments described.

None of these missions has been formally studied. The description of individual missions given in the following sections presents concepts rather than detailed system designs. Table 1 provides an overview of mission characteristics.

TABLE 1. Mission Summary

Mission	Spacecraft	Experimental Technique
Precision Doppler Tracking of Interplanetary Probes	Any Future Deep-Space Probe	Two-Way Radio Doppler
Doppler and Ranging Transponder (DART) Mission	One or Several Dedicated Deep-Space Probes	Two-Way Radio Doppler
Hydrogen Maser Gravitational Wave Probe	Single Deep-Space Probe	Four-Link Radio Doppler
Millimeter-Wave Interferometer	Three Satellites in Solar Orbit	Radio Wave Interferometer
Laser Heterodyne Gravitational Wave Antenna	Three Satellites in Solar Orbit	Laser Heterodyne Scheme
Laser Interferometer Gravitational Wave Antenna	Large Structure in Earth Orbit	Laser Interferometer

INTRODUCTION

The detection of gravitational radiation is an outstanding problem of major importance in physics and astrophysics. According to Einstein's General Relativity Theory (published in 1916), gravitational waves are generated when the mass quadrupole moment of some object or system experiences a change in time. For example, when a massive body undergoes asymmetrical deformation, energy is lost to space and propagates through space in a manner similar to electromagnetic waves.

Gravitation is the weakest of the four interactions in nature, and gravitational waves have never been detected. Nevertheless, because of the success of the General Relativity Theory so far, the existence of gravitational waves is generally accepted. The power radiated in gravitational waves as well as their effect on matter are extremely small. For this reason, the design of any type of gravitational wave detection scheme presents a considerable challenge.

A number of research groups are involved in the development of ground-based gravitational wave detectors. However, space experiments offer unique opportunities for detection of gravitational waves, and it may turn out that gravitational radiation can be detected only from space. This booklet describes several options for space investigations to search for gravitational radiation. Once this search has been successful, the developed techniques should evolve into a powerful tool for study of astrophysical phenomena.

SCIENCE

Extensive theoretical studies have been performed to identify potential astrophysical sources and mechanisms for generation of gravitational radiation and to estimate the intensity and frequency of gravitational waves arriving at the Earth.[1] Some potential sources of gravitational waves are listed in Table 2, together with the anticipated frequencies and strain amplitudes. While these estimates contain large uncertainties, they provide guidance in the search for gravitational radiation.

Gravitational waves cause forces that produce a strain in matter transverse to the direction of propagation. Because of their quadrupole nature, gravitational waves produce opposite strain in two mutually orthogonal directions which can excite free-mode oscillations in a bar-type antenna or a small displacement, ΔL, in a free-mass antenna (Figure 1).

The strain amplitude, $h = \Delta L/L$, provides a measure of the signal amplitude generated in a gravitational wave antenna. Table 2 indicates that, even for the strongest envisioned sources, the strain amplitudes and the resulting displacements are extremely small. In a free-mass antenna, the signal ΔL increases linearly with the antenna base line L (i.e., separation of the masses) for a given strain amplitude h. In space, very long baselines (millions of kilometers) are possible; therefore, increased detection sensitivity can be expected if noise sources increase more slowly with antenna length. The sources of greatest amplitude, and hence greatest promise of detection, appear to generate waves in the very low frequency (VLF) region with periods from seconds to hours. Detection of these VLF gravity waves is well suited to the very long antenna baselines possible only in space.

The sources listed in Table 2 produce gravitational wave bursts or monochromatic, continuous wave (CW) trains from a given direction in space. There is an advantage in looking for pulses in that they might have large amplitudes and therefore might be more easily detected. But there is also a disadvantage in that such pulses may be quite rare. Table 2 includes an estimate of the rate at which pulses might be expected. Although the largest pulses are infrequent, they appear to occur often enough to yield a reasonable probability of success during a space mission if adequate sensitivity of the detection

TABLE 2. Some Sources of Gravitational Radiation

Typical Sources	Period or Frequency	Expected Rate	Strain Amplitude (h)	Antennas Sensitive to Comparable Period or Frequency
Formation or Coalescence of Supermassive Black Holes	10 to 10^4 sec Burst	1 per wk to 1 per 300 yr	10^{-15} to 10^{-18}	Doppler Tracking of Interplanetary Spacecraft
Fast Rotating Binary Stars	10 to 10^4 sec CW	CW	$\sim 10^{-21}$	Laser Heterodyne and Interferometer Antennas in Space
Pulsars	0.1 - 100 Hz CW	CW	10^{-23} to 10^{-27}	Free-Mass Antennas in Space
Black Hole Formation or Coalescence Supernovae Collapse of Stars	100 Hz to kHz	> 1 per yr in nearby galaxies	10^{-18} to 10^{-21}	Ground-Based Antennas: Resonant Bar Antennas and Laser Interferometer

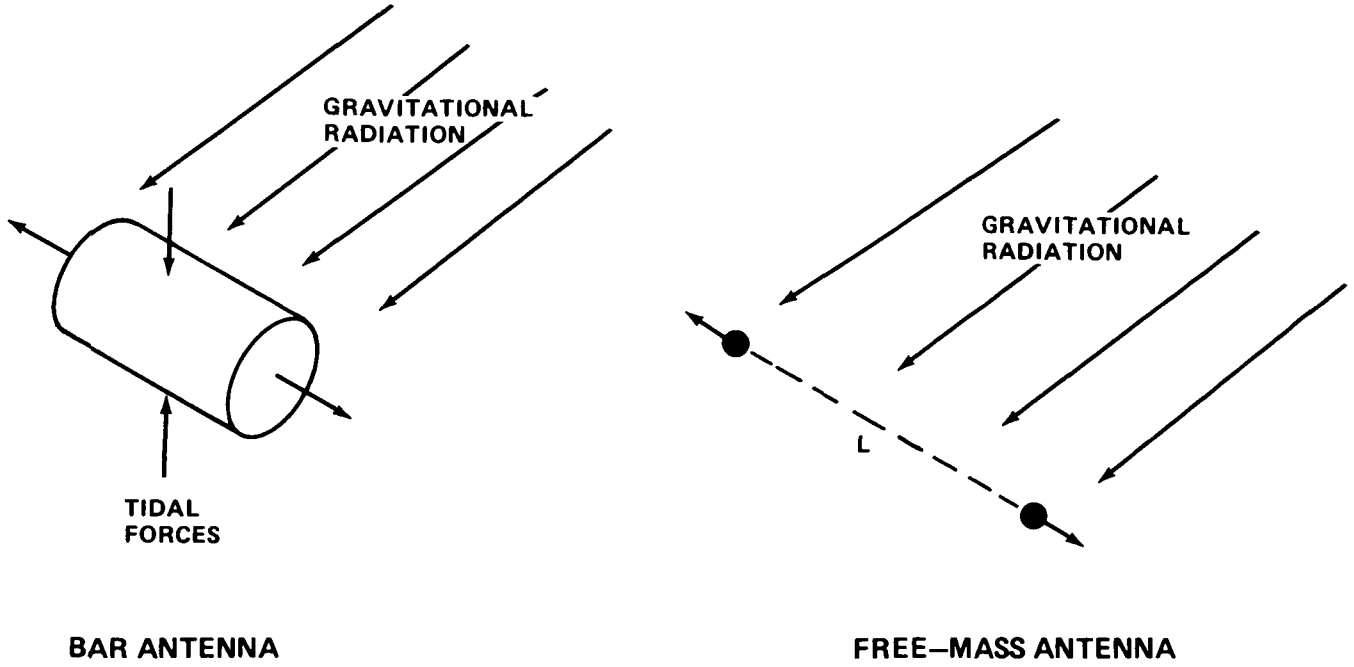

Figure 1. Gravitational Wave Antenna.

technique can be demonstrated. This topic is the subject of later sections.

In addition to the sources listed in Table 2, another type of radiation for which one may search is the ever-present background, the stochastic superposition of waves from all sources everywhere in the universe. An advantage of looking for the background is that it must always be present; therefore, data analysis techniques will be able to integrate deeply into other noise to detect the radiation. The strength of the background is important to cosmological model building, and even a null result (no radiation at the sensitivity level of a particular experiment) is important.

In summary, detection of gravitational waves is a very important scientific goal. It will provide an answer to the question of whether gravity should be described by a relativistic field theory. A failure to detect gravitational radiation from known sources would lead to a major revision of fundamental principles of physics, with implications in astrophysics and cosmology. On the other hand, the positive detection of gravitational waves will herald the opening of a new window on the universe: Gravitational Wave Astronomy. The only information presently available on the contents of interstellar or intergalactic space comes from electromagnetic radiation (except for a few cosmic rays). Yet many of the processes of greatest interest to astronomers today--processes such as the formation of black holes, explosions in galaxies, creation of quasars, etc.--are shielded behind layers of gas and dust that absorb electromagnetic radiation. Gravitational waves, on the other hand, pass readily through gas and dust and make these central violent events "visible". Also, since most large astrophysical objects are electrically neutral, the electromagnetic radiation from the object is the incoherent superposition of radiation from each of its small charged particles. Gravitational radiation arises from the large-scale motions of matter. The information it contains is therefore of an entirely different kind from that already available and may well revolutionize our understanding of astrophysical processes.

DETECTION TECHNIQUES

Space technology to search for gravitational waves can be divided into two categories, using either microwave Doppler tracking or laser measurements to detect the motion of free masses resulting from gravitatonal wave interaction. Information on typical missions employing these techniques is given in Table 3.

The Doppler tracking methods range in complexity from relatively simple additions on a planetary or other deep space mission to a dedicated spacecraft carrying an atomic clock, probably a hydrogen maser oscillator. Here the Earth serves as one of the free masses and a spacecraft as the other. The Doppler tracking is accomplished with the Deep Space Network (DSN).

The laser gravitational wave antennas employ three free masses in space in an interferometer-type configuration. Two antenna concepts have been proposed. One concept uses interferometry to detect the relative motion of the free masses; it is similar to a Michelson interferometer. The other concept uses a laser heterodyne technique to measure the distance change between the masses.

The options listed in Table 3 are further developed in subsequent sections. The key issue in each case is the strain sensitivity that may be achieved. Naturally, those techniques offering greatest sensitivity are likewise those requiring the greatest development effort. In each case, the expected sensitivity for the appropriate wavelength must be compared with the required sensitivity threshold for the corresponding wavelength from Table 2.

From a comparison of Tables 2 and 3, a fortunate circumstance can be noted. It is seen that the long wavelengths from the astrophysical sources

promising the greatest strain amplitude are also the wavelengths for which the best-developed space techniques have the greatest detection sensitivity. Thus, a systematic refinement of familiar Doppler tracking capabilities appears to be the best initial step toward a search for gravitational radiation. Feasible multiple-link Doppler tracking combined with the present stability of H-maser oscillators offers good prospects for successful detection. The definition phase of such a mission could begin at once. Successful measurements at any convenient wavelength can answer fundamental questions about the existence and nature of gravitational radiation.

Space technology for detection of shorter wavelength signals is less developed than that for the longer wavelengths. Still, the required advances, while challenging, seem attainable in time. The astrophysical importance of the sources at these wavelengths argues for an orderly research and development effort to reach the desired space capabilities. Once the threshold of gravitational wave astronomy has been crossed, impetus for advanced missions in this discipline will be strong.

In addition to the probability of gravitational wave measurements, a related matter is worth considering when evaluating a possible space mission. Namely, there are many other significant issues in gravitational physics besides radiation, and potentially a single mission can address some of these other issues as well as radiation. The opportunities for several other fundamental gravitational measurements are discussed in another booklet of this series (Relativistic Gravitational Experiments). In some cases, even the same spacecraft equipment can be used for multiple objectives, including a search for radiation. The performance of multi-objective missions can assure overall mission success even if an early radiation search should yield only a null result at some level of sensitivity. Realistically, it is doubtful that early radiation searches would or should be dedicated to that single objective.

TABLE 3. Typical Missions

Mission	Period (sec)	Strain Sensitivity	Development Considerations	Cost Considerations
Precision Doppler Tracking of Nondedicated Interplanetary Spacecraft	10^{4} to 10	10^{-14}	Modest Refinement of Conventional Doppler Tracking	Modest Incremental Cost
Doppler and Ranging Transponder Mission (DART)	10^{4} to 10	10^{-15}	Minor Development Effort	Minimal Dedicated Interplanetary Spacecraft
Hydrogen Maser Gravitational Wave Probe	10^{4} to 10	10^{-16}	Modest Development Effort	Dedicated Interplanetary Spacecraft
Laser Heterodyne Gravitational Wave Mission	10^{4} to 10	10^{-21}	Major Research and Development Effort	Substantial Function of Technology Advances
Laser Interferometer Gravitational Wave Mission	$>10^{2}$	10^{-21}	Major Research and Development Effort	Substantial Function of Technology Advances

PRECISION DOPPLER TRACKING OF NONDEDICATED INTERPLANETARY SPACECRAFT

OBJECTIVES

As various interplanetary missions are planned and performed, careful attention and modest augmentation to the two-way Doppler tracking aspects of the missions can provide an early opportunity to search for gravitational radiation. Mission lifetime and orbit will be determined primarily by planetary exploration objectives. Without dedicated systems, the strain sensitivity of such missions is unlikely to reach the threshold where detection of gravitational radiation is highly probable; but, if actual amplitudes are unexpectedly high, they could be detected.

The four objectives of precision Doppler tracking during nondedicated interplanetary missions would be:

(1) Search for very large-amplitude, VLF gravitational pulses emitted from catastrophic astrophysical events

(2) Detect, or put upper bounds on, a possible stochastic, cosmological background of gravitational waves produced in the early history of the universe

(3) Demonstrate Doppler spacecraft tracking as a unique, broadband detection technique for VLF gravitational waves

(4) Develop the technology and improve the sensitivity of Doppler tracking.

INSTRUMENTATION

Spacecraft instrumentation for these missions includes S-band and X-band transponders, with modest refinement of performance parameters. The development of higher frequency (X-band) Doppler uplink is in progress.

The DSN with extremely stable atomic clocks is the counterpart to the spacecraft instrumentation. Preliminary studies are under way to determine required modifications to the DSN for improving frequency stability and increasing Doppler tracking precision.

MISSION DESCRIPTION

Doppler detection of gravitational radiation is a multimission program that can be undertaken as a radio science objective on all future deep space missions. Initial feasibility experiments are under consideration for several early mission candidates. Improved experiments can be implemented on other future deep space missions, leading eventually to a dedicated mission devoted primarily, or even exclusively, to gravitational wave astronomy, as described later.

DOPPLER AND RANGING TRANSPONDER (DART) MISSION

OBJECTIVES

The Doppler and Ranging Transponder (DART) mission would be dedicated to gravitational physics investigations. The mission has two science objectives: a search for gravitational waves and measurement of the relativistic time delay. Gravitational radiation from known continuous wave sources is too weak to be detected with radio Doppler techniques. The DART mission will concentrate on gravitational bursts from big events. Strain amplitudes of $h = 10^{-15}$ or larger should be detectable with DART. In addition, DART will search for gravitational background radiation in the 10^{-4} to 10^{-1} Hz band.

The technique of using Doppler tracking as a gravitational wave antenna is now well known.[2] Experiments tracking near-term spacecraft are either planned or in progress. The limiting noise sources in these experiments at the spectral frequencies of interest are interplanetary plasma scintillation, troposphere scintillation, and spacecraft buffeting. The purpose of this mission is to produce a spacecraft that reduces all these noise sources to a part in 10^{15}. The plasma scintillation will be reduced by using dual S/X frequency tracking on both uplink and downlink. Differencing the Doppler signals at these two frequencies allows for the calibration of the total electron content along the path of the radio signal. The tracking signal may then be corrected to account for these effects throughout the trajectory (except for lines of sight very close to the Sun). Spacecraft buffeting (nongravitational forces) will be reduced by using a dense spacecraft impervious to fluctuations in solar radiation pressure, by having no competing on-board mechanical motion, and by reducing attitude correction maneuvers to an insignificant level. Troposphere scintillation effects will be corrected for by using the water vapor radiometer techniques presently being integrated into the DSN stations.

Although not strictly a topic for this booklet, a second scientific investigation can most appropriately be performed with the same spacecraft equipment. This investigation is the measurement of the time delay produced in an electromagnetic signal passing close to the Sun. This is an important test that can differentiate among various competing theories of gravity. Despite its general acceptance as the correct theory of gravity, General Relativity rests on a somewhat weaker experimental base than do most other accepted theories of fundamental physical interactions. The relativistic time delay that can be measured with the DART should be able to constrain theories far more strongly than has been done in the past. Because of its dense character, the spacecraft resistance to nongravitational forces should allow for an extremely accurate orbit determination (errors of less than 1 m over periods of several days). The dual-frequency ranging system will permit calibration of the plasma-induced phase delay. The resulting accuracy in the time delay should be a few parts in 10^5, which is better than an order of magnitude improvement over existing experiments.

INSTRUMENTATION

The pertinent instrumentation and equipment on board the spacecraft consist of:

(1) 1.4 m, high-gain parabolic antenna with S- and X-band feeds

(2) State-of-the-art NASA standard S- and X-band transponders, including ranging systems

(3) RTG power system delivering 60 W total power at $\sim$10 V

(4) Cold gas attitude control system to process the spin-stabilized antenna axis.

These systems, of course, need to be configured to meet the $h = 10^{-15}$ strain amplitude objectives discussed previously.

In the DART design the only item of new technology that is not standard on existing deep space missions is the dual-band receiving capability. Even if not developed for earlier missions, this should offer no design difficulty. All other systems require only minor modifications of existing hardware.

MISSION DESCRIPTION

One or more dense, RTG-powered, spin-stabilized spacecraft, equipped with S- and X-band low-noise transponders and high-gain antennas, are to be placed in heliocentric orbit at approximately 5 AU. The spacecraft are Doppler and range tracked with the DSN to determine accurately their orbits and the small transient velocity effects of gravitational waves. Dual frequencies on both uplink and downlink allow for calibration of the integrated plasma effect. Table 4 gives characteristic parameters for the spacecraft.

TABLE 4. Spacecraft Parameters

Spacecraft Mass	150 kg
Generated Power	600 W
Radiated Power	20 W
Optical Cross Section	0.6 m^2

The assembled spacecraft (Figure 2) will be fitted into a standard PAM-D upper stage, and the package will be Shuttle launched. In Earth orbit, the spacecraft and upper stage will be spun up to approximately 60 rpm and then launched into free heliocentric ecliptic orbit with aphelion at 5 AU and perihelion at 1 AU.

When the spacecraft nears solar conjunction and solar plasma scintillation begins to degrade the Doppler for gravity wave purposes, ranging and complete orbit determination coverage will begin for purposes of the gravitational time delay experiment.

Lifetime of the nominal mission will be 10 years, limited mainly by the amount of attitude control gas to be carried.

FUTURE OPTION

The design of the DART has been chosen to reduce noise to a level of 10^{-15} while retaining proven, conventional spacecraft and tracking methods. An increase in sensitivity to the 10^{-17} level is a reasonable goal, however, with a millimeter wave interferometer, as shown in Figure 3. The free spacecraft would be of the same basic design as the DART, with a 300 GHz, 60 cm antenna and electronics replacing the dual S- and X-band systems. The interferometer configuration is necessary to reduce noise from clock jitter to the required level, while the spaceborne tracking station is dictated by the need to avoid troposphere scintillation. The higher radio frequency will reduce the plasma noise to the desired level.

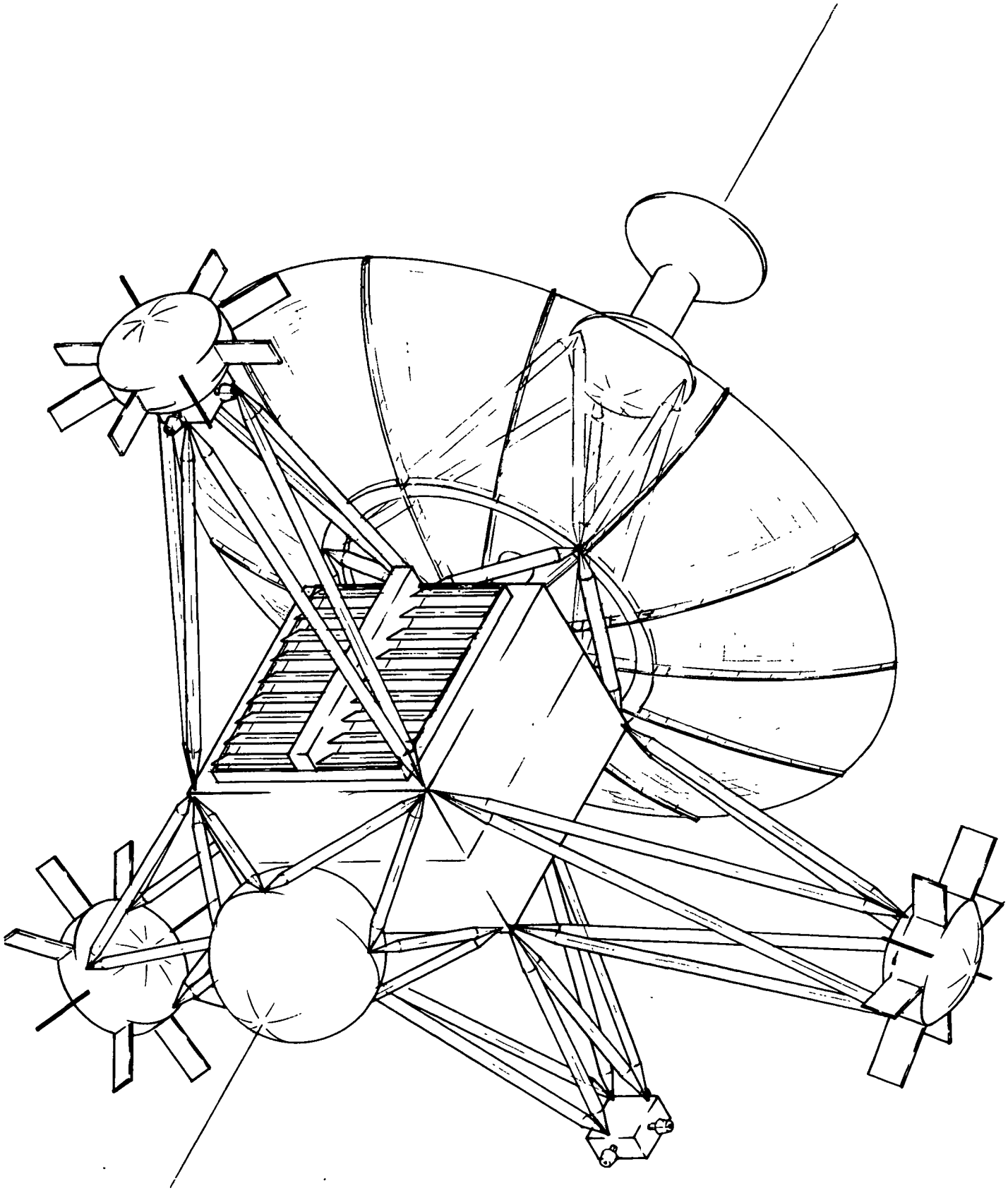

Figure 2. DART Spacecraft.

DOPPLER AND RANGING TRANSPONDER (DART) MISSION

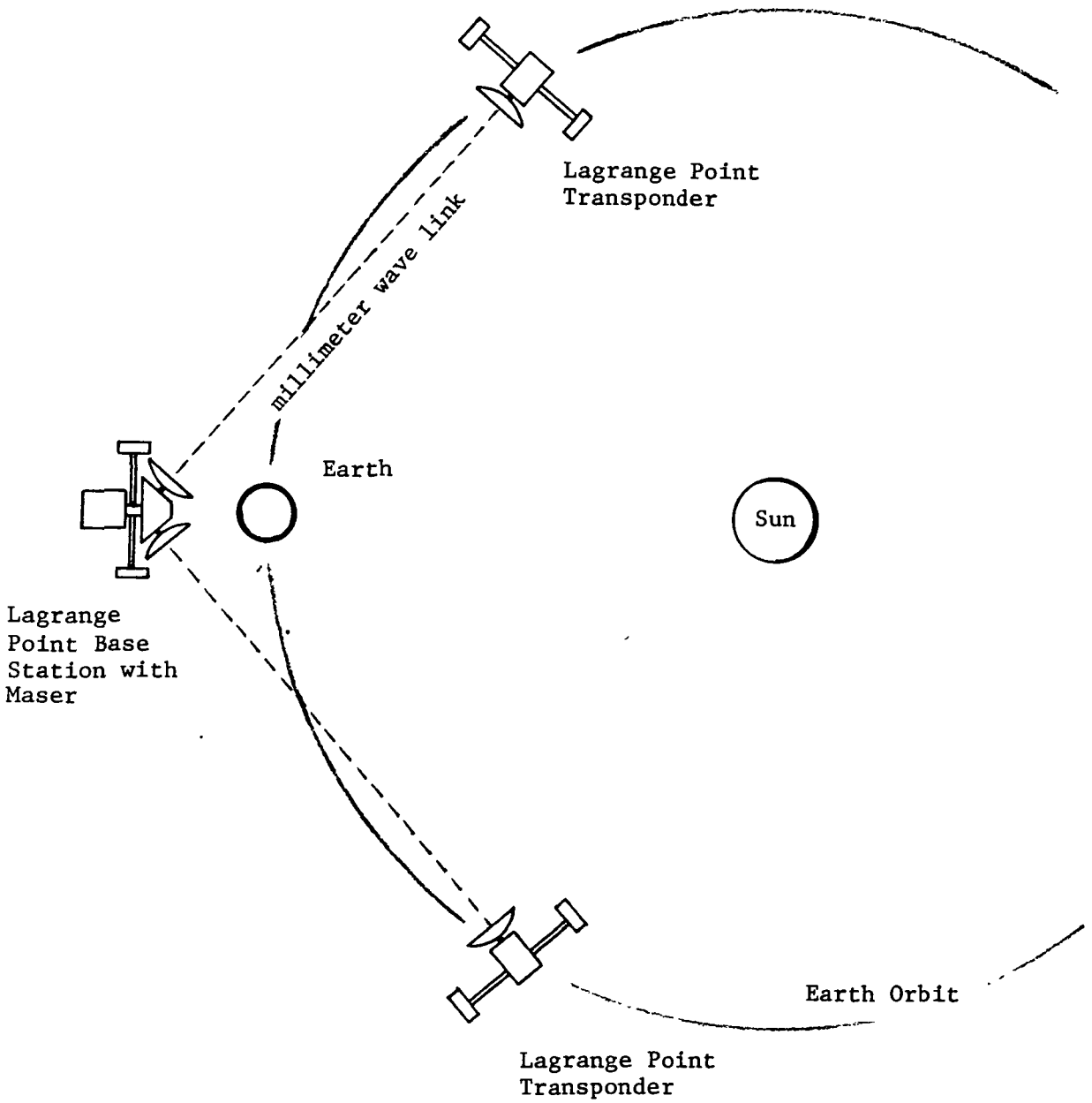

Figure 3. Millimeter Wave Interferometer.

HYDROGEN MASER GRAVITATIONAL WAVE MISSION

OBJECTIVES

This mission goes beyond those described in the two previous sections in that it includes hydrogen maser oscillators in the spacecraft and ground station and employs a fourlink microwave system. This added capability is designed to attain $h = 10^{-16}$ strain sensitivity.[3]

The main objective of the mission is a search for gravitational radiation in interplanetary space, but, as with DART, other gravitational objectives are natural companions. A gravitational redshift measurement in an initial highly eccentric Earth orbit is one such possibility (see Relativistic Gravitational Experiments booklet).

The method employed for detection of gravitational radiation is again precision Doppler tracking. The goal is the detection of extremely low-frequency pulses of gravitational radiation originating from collapsing, supermassive objects (10^6 to 10^7 solar masses). Potential sources of this type of gravitational wave burst are the formation of black holes in the cores of ordinary spiral galaxies. It is believed that these events occur frequently enough to be detected more than once per year during the proposed mission, given the 10^{-16} strain sensitivity.

The passage of a gravitational radiation pulse causes phase changes in the four microwave links and generates a unique sequence of ten pulses that allows identification of the gravitational wave burst. This situation applies when the signal propagation time, $\tau = R/c$, between the Earth and spacecraft is long compared with the time interval characterizing the gravity wave event. Time correlation and pattern-recognition methods applied to the data sets from the four links permit identification and removal of disturbances resulting from clock jitter, antenna motion, spacecraft buffeting, and signal propagation anomalies.

INSTRUMENTATION

Figure 4 is a schematic of the symmetrical four-link microwave system to be used in this mission. The four signal links, each at a different frequency, are shown separated, but, in reality, they share the same antenna. The system is completely phase coherent. The oscillators (hydrogen maser clocks) serve as proper clocks and local oscillators for the receiver and as master oscillator for the transmitter. The system is completely symmetrical with respect to signals. The ground clock signal is returned to the ground station by the spacecraft transponder, while the space clock signal is returned to the spacecraft by the ground station transponder. The system operates at X-band with a single S-band auxiliary link which is phase coherent with one X-band link to allow measurement of the columnar electron density in the ray path (for *a posteriori* ionospheric corrections).

A gravitational wave pulse appears as a unique ten-pulse sequence in the four signal links. Figure 5 illustrates the responses of the four signals to a gravitational wave burst which intersects the baseline at an angle θ.

The hydrogen maser oscillators for this mission would be substantially improved versions of those flown successfully in 1976 on the Gravitational Probe A (GP-A) mission. Hydrogen maser technology has advanced by at least an order of magnitude since 1976. The GP-A mission also carried a three-link microwave system, of which the four-link system is a direct extension.

MISSION DESCRIPTION

The basic spacecraft design will be similar to that of the DART spacecraft except for a somewhat larger size to accommodate the hydrogen maser clock.

The solar orbit inclination should be rather small, and the maximum

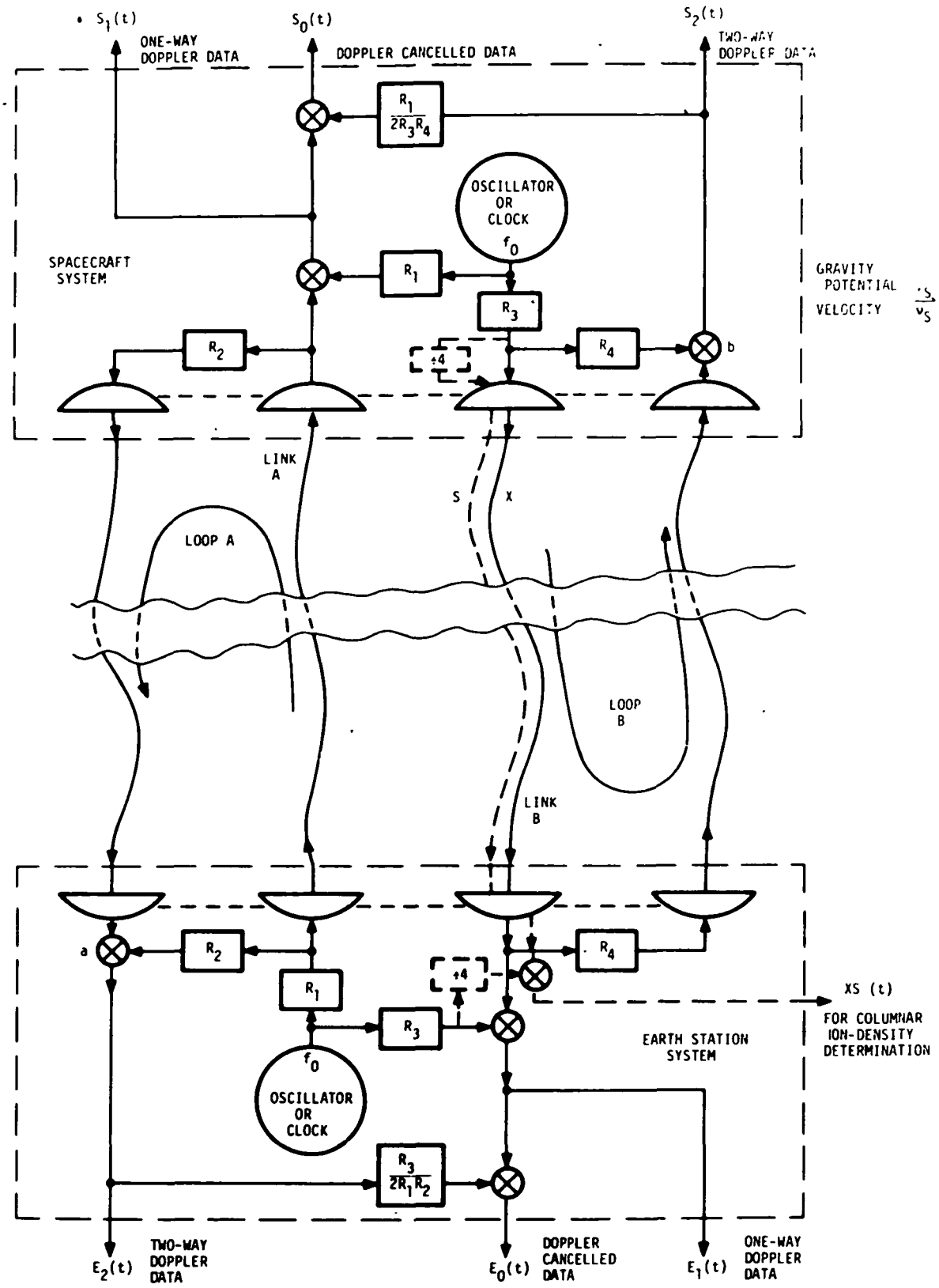

Figure 4. Four-Link Microwave System.

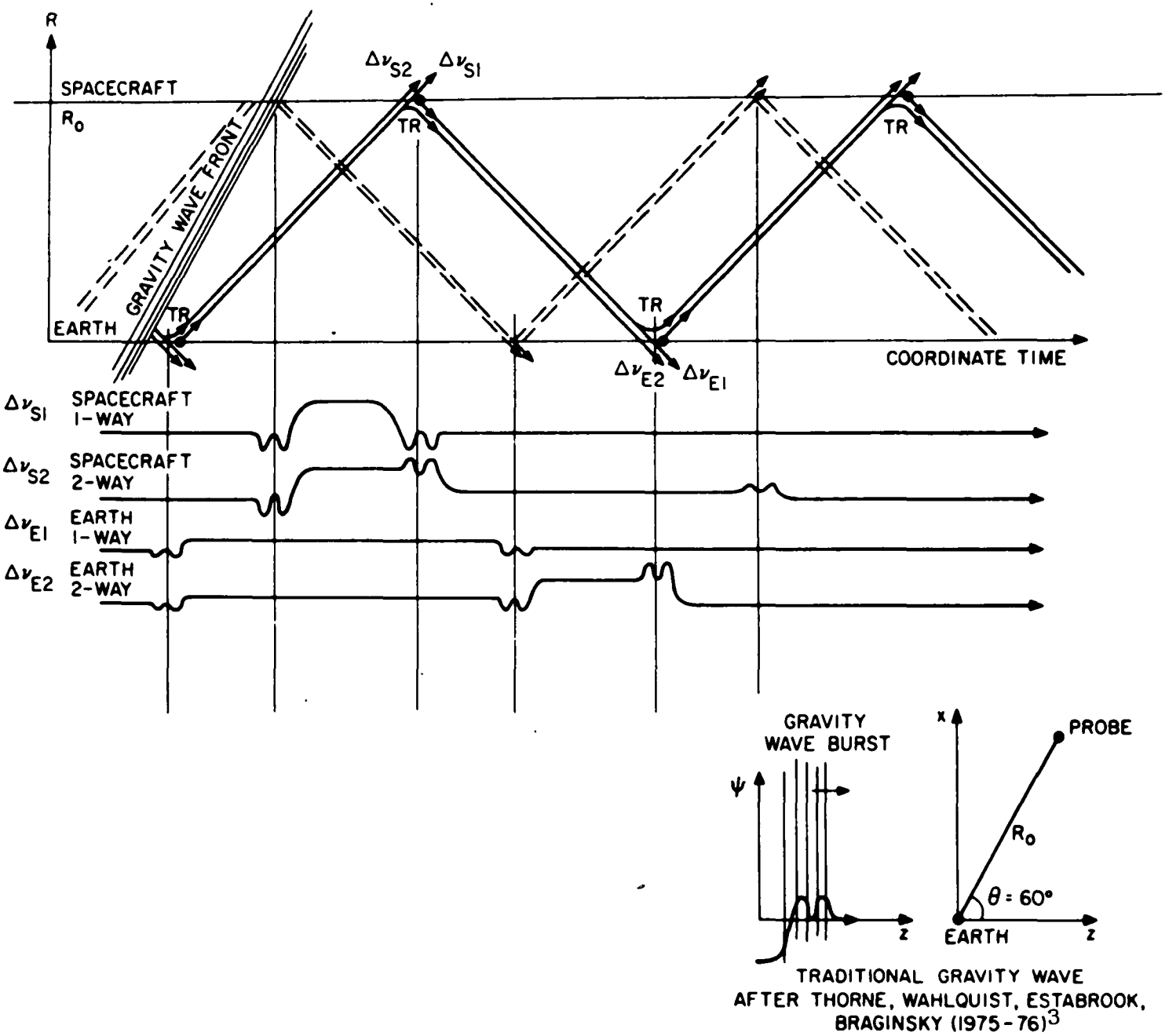

Figure 5. Gravitational Wave Response of Four-Link System.

distance from the spacecraft to the Earth should reach at least 6 AU. During the time of maximum separation between Earth and spacecraft, the angle between the Earth-Sun line and the Earth-spacecraft line should be as large as possible to reduce disturbances from the solar wind plasma. A substantial amount of DSN observing time will be needed because of the estimated low event rate of gravitational radiation bursts. Nearly continuous tracking coverage involving more than one ground station is very desirable.

LASER HETERODYNE GRAVITATIONAL WAVE MISSION

OBJECTIVES

The configuration of the laser heterodyne gravitational wave mission is illustrated in Figure 6. It consists of three spacecraft (S1, S2, S3) in circular orbits around the Sun with periods close to 1 Earth year. The two subspacecraft, S2 and S3, are in the same orbit, while the main spacecraft is in an orbit slightly inclined to the subspacecraft orbit. Two-way laser signals are transmitted between the main spacecraft (S1) and each of the subspacecraft, which are separated from S1 by 10^6 km. Each spacecraft contains a laser transmitter that serves also as local oscillator. A distance change between the spacecraft caused by gravitational waves is detected by a heterodyne technique.

The objective of this mission is the detection of gravitational radiation from fast-rotating binary stars with strain amplitudes of approximately 10^{-21} and gravitational wave periods of minutes to hours. In addition, long-period gravitational wave bursts and background radiation with strain amplitudes $> 10^{-21}$ can be detected.

The laser heterodyne technique proposed to measure distance changes between the spacecraft appears to permit much larger antenna baselines than would be possible with the interferometer scheme discussed previously.[4] The gravitational wave signal increases linearly with the antenna baseline, while some noise sources increase more slowly, resulting in a more sensitive gravitational wave detector.

The laser gravitational antenna would have the ability to measure the speed of propagation of gravitational waves to 10^{-7} or better and to determine the polarization of the waves. These measurements would make it possible to check certain theories of gravitation that agree with General Relativity Theory except for those two properties.

INSTRUMENTATION

Distance changes between the spacecraft resulting from gravitational wave interaction will be measured by a laser heterodyne technique. Each spacecraft has its own laser oscillator-transmitter. Also, at each spacecraft, the beat frequency between received signals and local oscillator signal is generated. This information is telemetered from the two outer spacecraft to the central spacecraft. Proper combination of the beat signals will yield the difference in lengths of the two arms S1,S2 and S1,S3. For utmost sensitivities, the length of the two arms should be nearly equal. Shielding of the spacecraft from solar wind and other disturbing forces is needed, including the application of drag-free control system techniques. Cosmic GeV protons are a major noise source. With 5 mW laser beams from 0.633 μm cavity-stabilized helium-neon lasers and receiving telescopes 100 cm in diameter, averaging times of approximately 10^3 sec would be needed to detect a 10^{-8}-cm amplitude in distance (if no other noise sources were present).

MISSION DESCRIPTION

The three spacecraft will be placed in a circular heliocentric orbit with a period of 1 Earth year. The three spacecraft will remain in the vicinity of the Earth while orbiting the Sun. Occasional thrust maneuvers are required for the main spacecraft to maintain the desired relative configuration. For initial setup, microwave tracking from the Earth will be sufficient. Each spacecraft will be equipped with a propulsion system to perform the necessary maneuvers. Since the spacecraft will remain in the vicinity of the Earth, this proximity allows easy communication and data transmission between the gravitational wave antenna and the Earth.

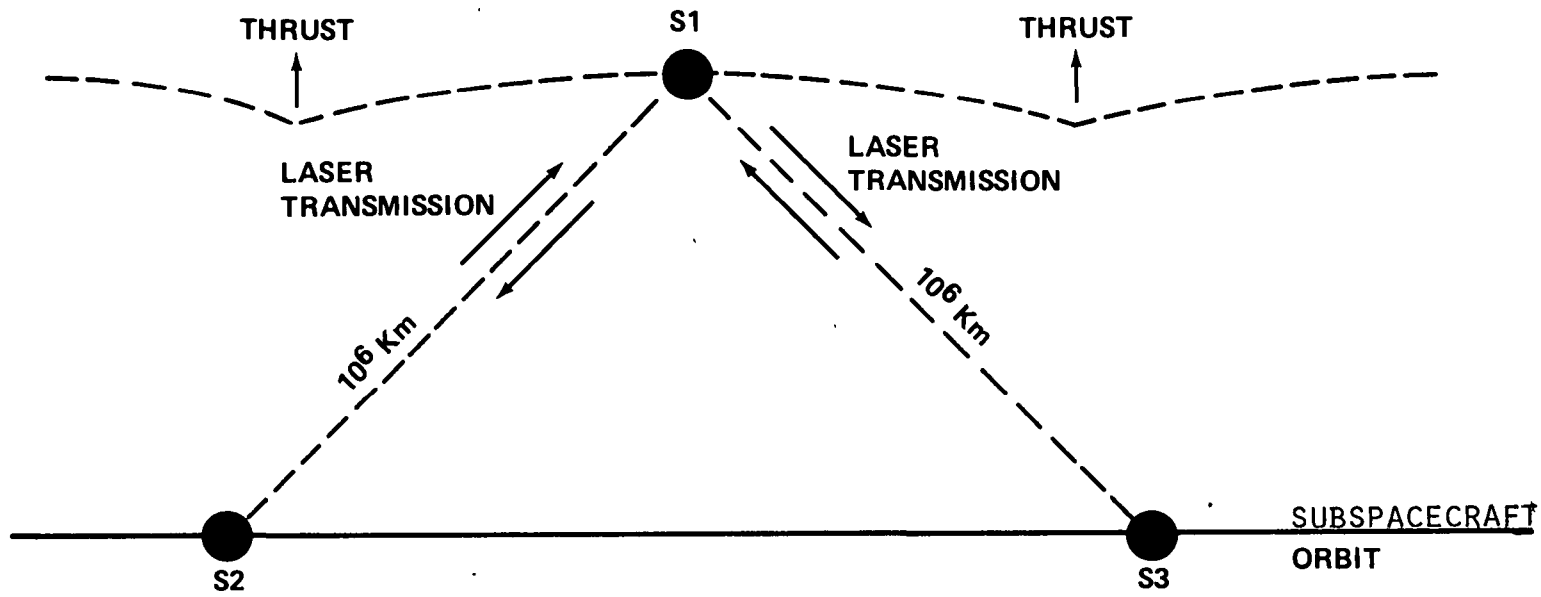

Figure 6. Laser Heterodyne Gravitational Wave Antenna.

LASER INTERFEROMETER GRAVITATIONAL WAVE MISSION

OBJECTIVES

The objectives of the laser interferometer mission are:

(1) To search for gravitational radiation from fast stellar binaries as well as other sources permitted by an optimal antenna design

(2) To determine the characteristics (i.e., frequency bandwidth, duration, and polarization) of the radiation

(3) To detect the time history of amplitude, frequency, and phase of short bursts of radiation.

A gravitational wave antenna design that has shown some promise in initial studies is a Michelson interferometer mounted on a large structure placed in Earth orbit. The antenna masses, loosely suspended on the structure by field suspension, serve as mirror mounts in multipass interferometer arms. A symmetric arrangement of interferometer arms reduces many of the systematic noise terms. Measurement of the gravitational strain using the relative displacement of the antenna masses is made via fringe shift phase displacement between two interferometric mirrors using a high-powered laser as the light source.

Among the advantages of this type of configuration is the fact that major noise sources may not scale with the baseline, while the signal-to-noise ratio for detection of the radiation will scale with the square of the baseline up to dimensions comparable with the wavelength of the gravitational waves being sought.

INSTRUMENTATION

The gravity wave interferometer structure is fabricated in space using a "beam machine". The critical features of the antenna structure are arm dimensions of 1 km, the capability of supporting a metric ton of mass at each corner, and the longest resonant period being much less than and well separated from the gravitational wave period. The beams form the primary members of this large structure, with wires in tension adding to its stiffness.

The concept of a laser interferometer gravitational wave detector has been studied.[5] The major components of the antenna are shown schematically in Figure 7. The antenna is basically a Michelson interferometer with mirrors serving as optical delay lines and arranged as shown in Figure 7. The laser beam is split along each arm and enters the spherical mirrors through a hole in the reflective coating of the first mirror. This beam makes multiple passes along the arm, hitting different points on the mirror until it is refocussed and passes through another hole in the first mirror's coating. This beam is recombined with the beam from the other arm and passes to a photodetector.

One of the detecting masses is held on a fixed fringe by a servo system. The servo output signal is proportional to the differential strain and is obtained by modulating the optical phase in one arm with a Pockel-effect phase shifter.

The photosignal at the modulation frequency is synchronously detected, filtered, and applied to two controllers: a fast controller for high frequencies, and a slow, large-amplitude controller to compensate for thermal drifts and large-amplitude, low-frequency noise. The data are then processed and telemetered to Earth.

Gravitational radiation must be detected in the presence of noise produced in the antenna both naturally from the environment and by the antenna and its systems. Some of the identifiable noise sources present in an antenna in space are:

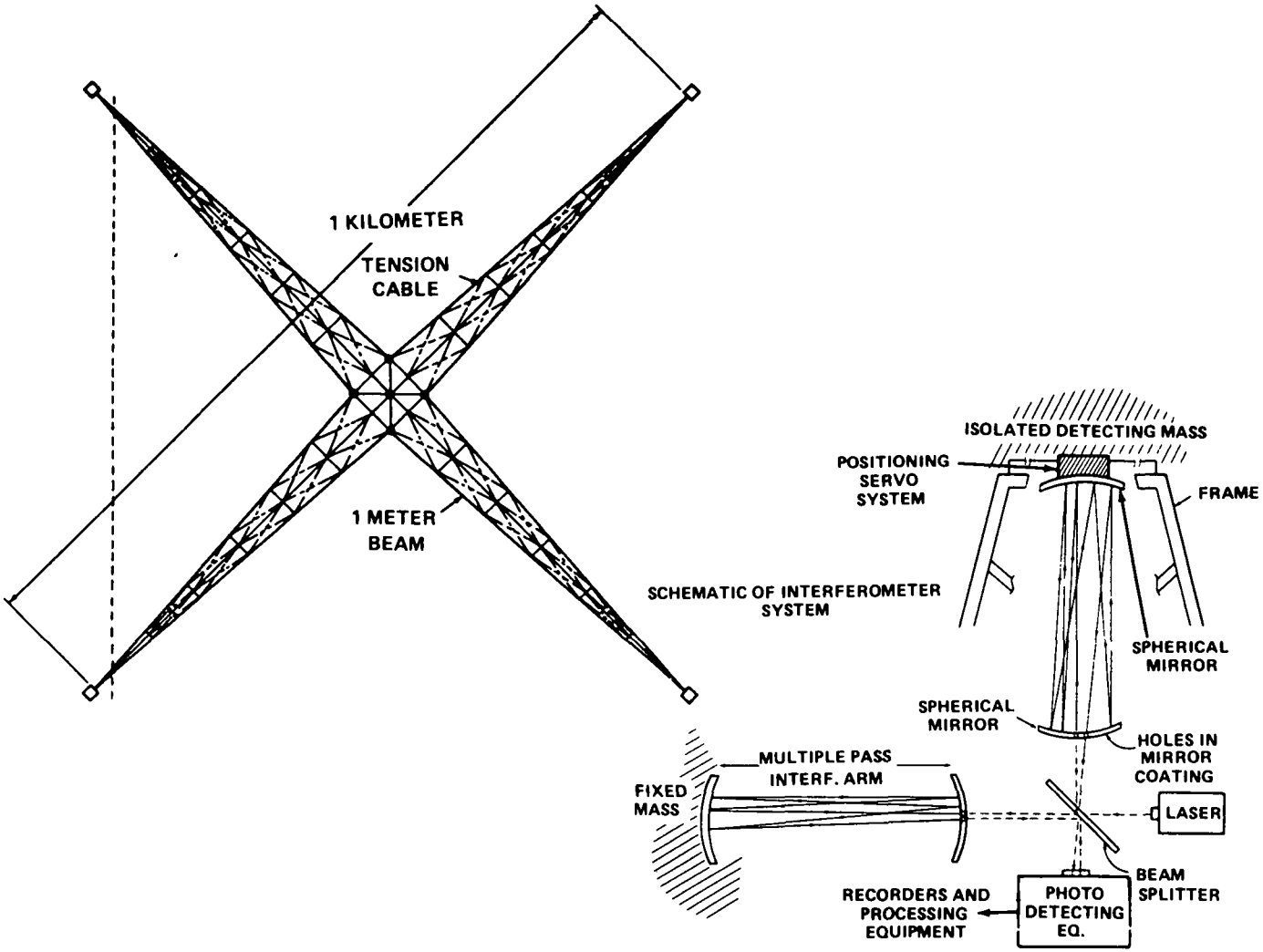

Figure 7. Schematic of Gravitational Wave Interferometer.

(1) Cosmic Rays

(2) Thermal Gradients

(3) Gravity Gradients

(4) Electric and Magnetic Fields

(5) Pointing and Control System

(6) Solar Radiation Pressure

(7) Radiation-Pressure Noise from Laser Light

(8) Mechanical Vibrations

(9) Amplitude Noise in Laser Output Power

(10) Laser Phase Noise or Frequency Instability.

At low frequencies, many noise sources due to stochastic forces are larger than the oscillator amplitude noise; the dominant noise appears to be the random forces of cosmic-ray protons. Cosmic-ray proton noise may be reduced by using large (1000 kg) detecting masses.

MISSION DESCRIPTION

The payload is launched by the Shuttle into low Earth orbit. The antenna structure is fabricated by the beam manufacturing machine designed to fit in the Shuttle cargo bay. This machine will be fed strip metal from large rolls and will form this material into long beams in a continuous process.[6] Each beam is an open structure of triangular cross section 1 km on a side. The vertices of the triangle are sections of the strip metal shaped by the machine. These are connected by cross braces attached as the shaped metal leaves the machine. This concept is depicted in Figure 8. The antenna is assembled and aligned, and checkout of all systems is performed.

After stabilization of the antenna, the initial phase would be devoted to a general search for gravitational radiation. Later, specific astrophysical objects, such as a binary star system, would be investigated. In this mode, the antenna would be pointed normal to the source, and data would be taken over a period of time. For example, a sample calculation for this antenna indicates that approximately 10 days of integration time would be necessary to measure the estimated gravitational strain of $> \ell/\ell \sim 10^{-21}$ from a stellar binary that has a 40-min period.

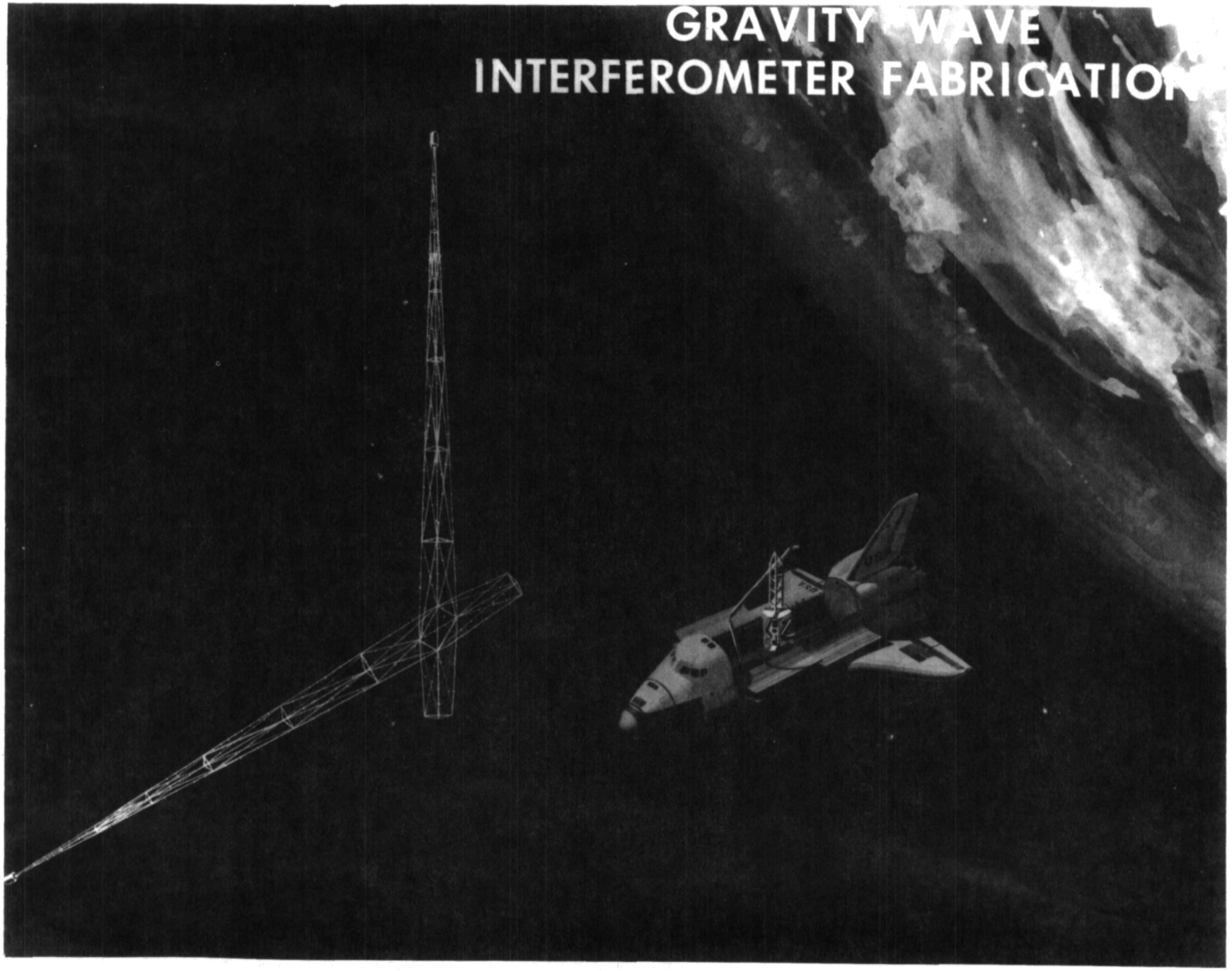

Figure 8. Gravity Wave Interferometer Fabrication Concept.

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